Neutrino hierarchy from cosmology

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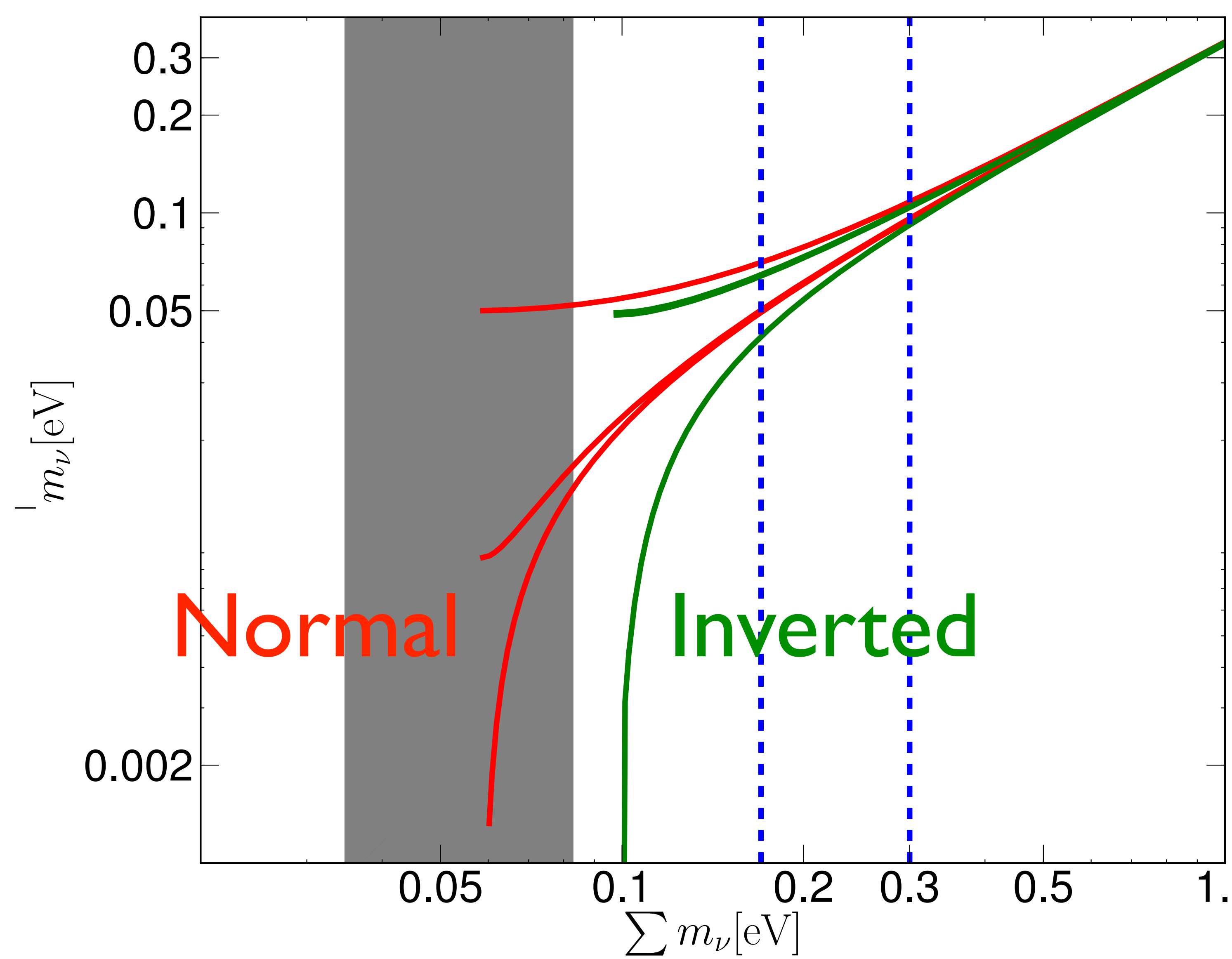
Sum of masses vs. hierarchy

- Key fact: Large-scale structure cosmology only measures the sum of neutrino masses.

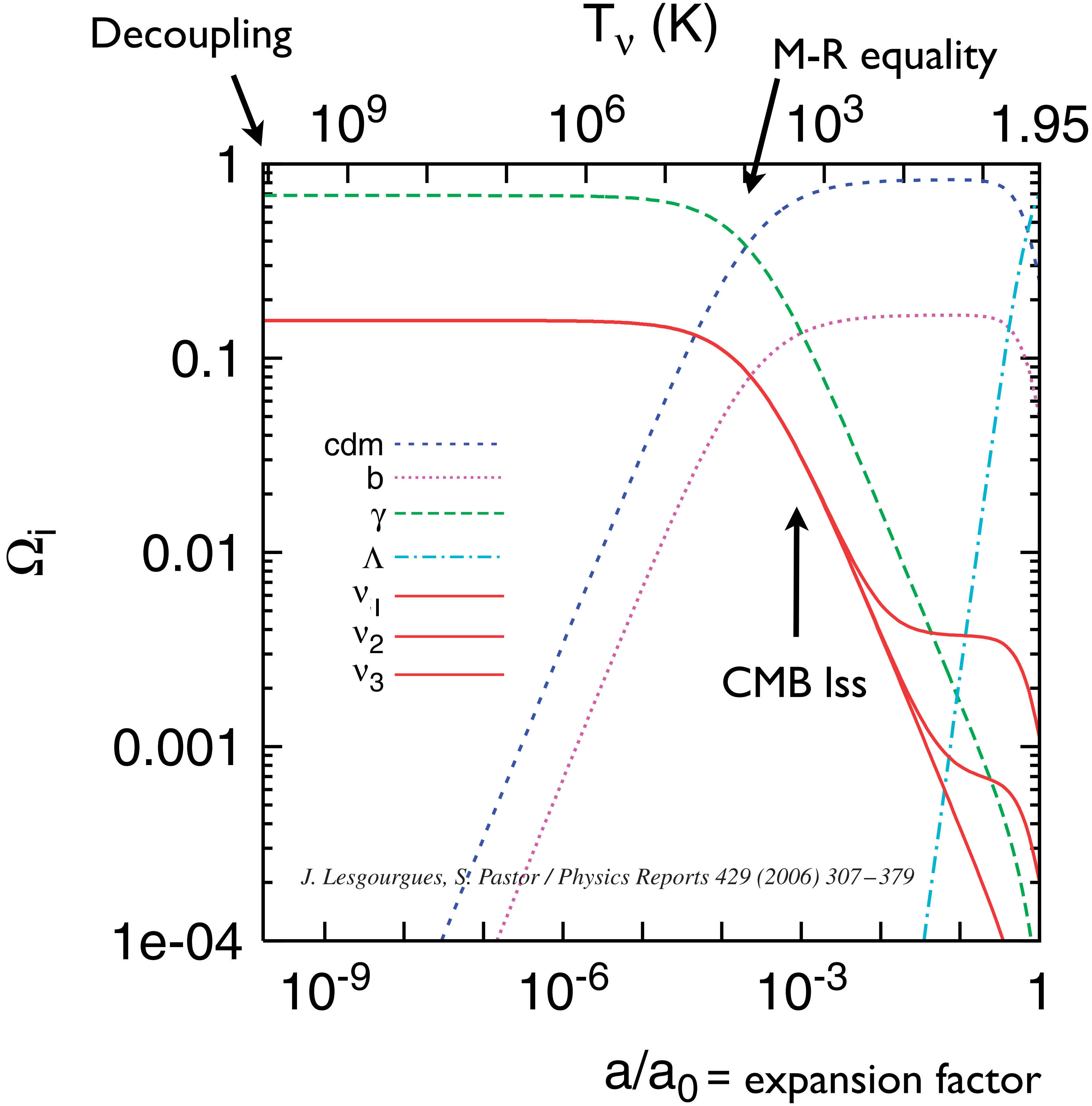
- Known mass differences:
  - 0.009 eV
  - 0.048 eV

- Minimum total mass:
  - normal: 0.057 eV
  - inverted: 0.105 eV



All LSS can do is identify a minimal mass normal hierarchy

Densities vs. time



$$\rho_\nu^{\rm nr} = m_\nu n_\nu$$

$$z_{\rm nr} \sim 94\ (m_\nu/0.057\ {\rm eV})$$

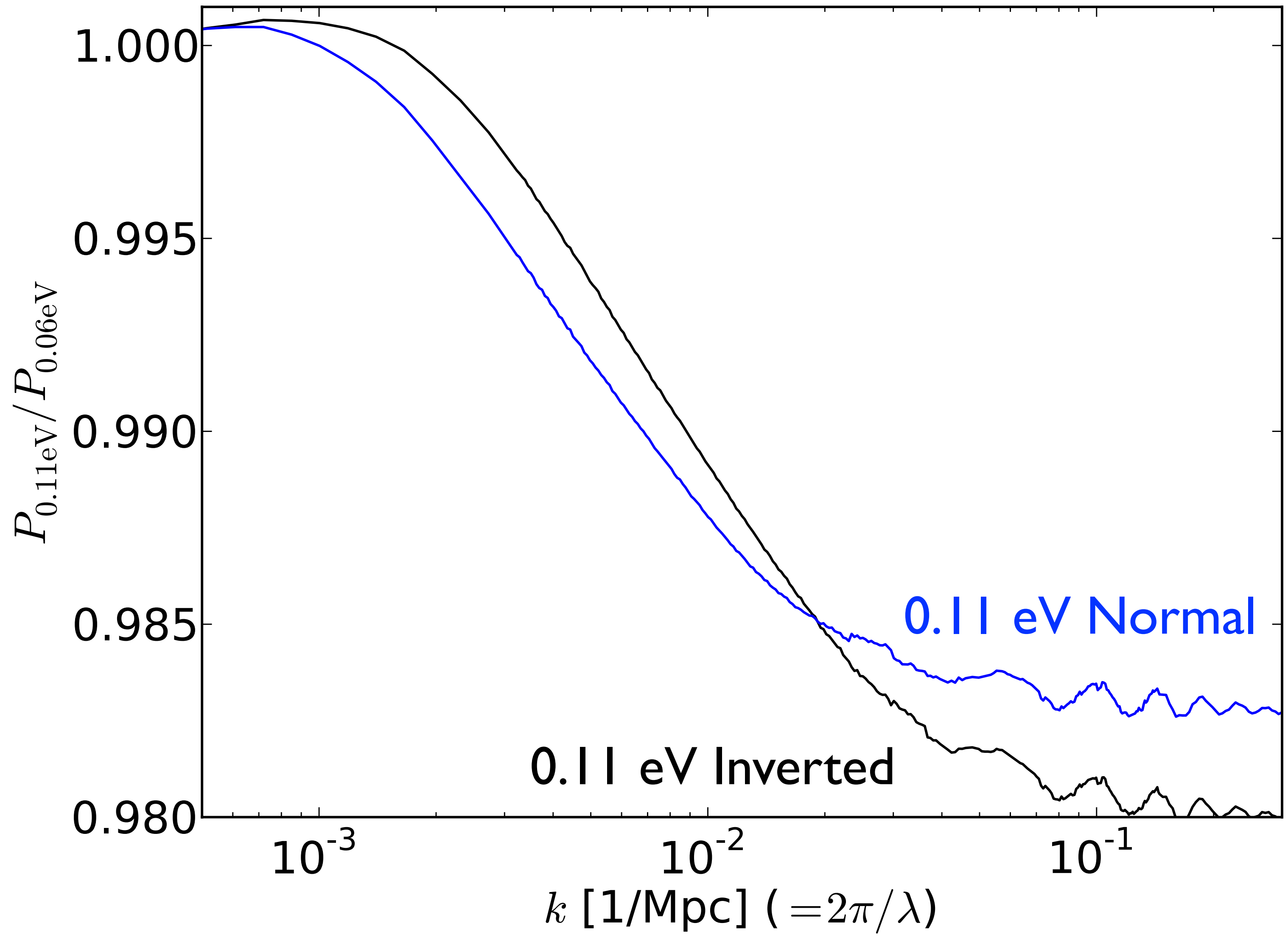
$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = 0.00125\left(\frac{m_\nu}{0.057{\rm eV}}\right)\left(\frac{h}{0.7}\right)^{-2}$$

Presently >0.4% of matter density

Neutrino suppression of power

$$v_{\rm rms} \simeq 3173\,(1+z)\,(0.057\,{\rm eV}/m_\nu)\;{\rm km\ s^{-1}}$$

- Only at z~100 does a 0.05 eV neutrino finally become non-relativistic.
- Contribute to the subsequent background evolution as if they were dark matter.
- Don't cluster except on very large scales.
- Mass perturbations are "underweight" and don't grow as fast as they would for pure CDM.



$$P(k) \propto \left\langle |\delta_{\mathbf{k}}|^2 \right\rangle \propto {\rm FT}\left[\langle \delta(\mathbf{x})\delta(\mathbf{x}+\mathbf{r})\rangle\right]$$

- Measure this suppression in various ways:
  - Gravitational lensing of the CMB by foreground mass
  - Lensing of galaxies
  - Number of galaxy clusters
  - Large-scale clustering of galaxies

Galaxy clustering

- Galaxy density proportional to mass density on large enough scales.
- Power errors easy to estimate given volume, number density and bias.

$$\left[\frac{\Delta P_{\rm g}}{P_{\rm g}}\right]^2 = \frac{2(2\pi)^2}{V_{\rm survey} k^2 \Delta k \Delta\mu}\left[1+\frac{1}{n_{\rm g} P_{\rm g}}\right]^2$$

- Propagating to neutrino mass errors relatively straightforward but involved (angle and redshift dependence, include CMB, marginalize over other parameters).
- Dark Energy optimized surveys like BigBOSS or Euclid are also optimal for neutrinos.

Experiments

- Planck CMB results nail down the high-z Universe, including contents and initial power spectrum.

BigBOSS/MS-DESI

- LBL-led redshift survey
- 14000 sq. deg.
- ~20 million galaxies and quasars at z=0-3.
- 2018-2022 (at which point it may be possible to move the spectrograph to cover more area).

Euclid

- European led satellite with LBL members
- redshift survey and gravitational lensing (latter sub-dominant for neutrinos)
- 15000 sq. deg.
- ~50 million galaxies at z=0.6-2
- ~2020-2026

LSST

- Ground-based imaging survey aimed at gravitational lensing.
- 20000 sq. deg.
- ~2022-2032

Projected constraints

Table 2: Potential constraints on the sum of neutrino masses, Σm_ν, for the minimal parameter set. P means Planck CMB data has been included. Numbers in parentheses are maximum k used for galaxy clustering, in units of Mpc^{-1}. This has LSST lensing but no Lyα forest. BigBOSS14 vs. 24 means 14000 or 24000 sq. deg. (after the first uses we shorten BigBOSS to BB). From the Euclid satellite (sometimes shortened to Euc) we use only the redshift space clustering information, not lensing.

Conservative case

	$k_{\max}$ $[\mathrm{Mpc}^{-1}]$	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{0.05\mathrm{eV}}$	Year Year(?)
P+BigBOSS14	0.07	0.0232	2.2	2022
P+Euclid	0.07	0.0208	2.4	2026
P+BigBOSS24	0.07	0.0192	2.6	2026
P+BB24+Euc	0.07	0.0165	3.0	2026
P+BB14+Euc+LSST	0.07	0.0142	3.5	$\lesssim 2030$
P+BB14	0.14	0.0142	3.5	2022
P+Euclid	0.14	0.0130	3.8	2026
P+BB24	0.14	0.0122	4.1	2026
P+BB24+Euc	0.14	0.0105	4.8	2026
P+BB24+Euc+LSST	0.14	0.0091	5.5	$\lesssim 2030$
WFIRST?				
Euclid lensing and clusters?				
CMB lensing?				
21 cm intensity mapping? (fastest if it works?)				

Realistically optimistic case

Conclusions

- *If* the neutrino hierarchy is normal with minimal masses, cosmological large-scale structure measurements will almost surely measure this to 3-5 sigma significance by 2026-2030.
- With good theoretical modeling progress, it is possible that BigBOSS could achieve 3+sigma by 2022 (LBL can lead all aspects of this).
- If the sum of masses is much above the minimum, cosmology will not probe the hierarchy.